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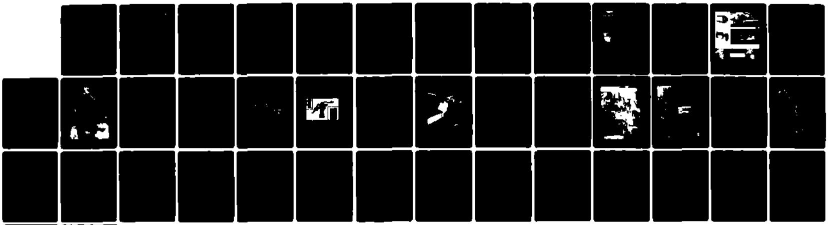

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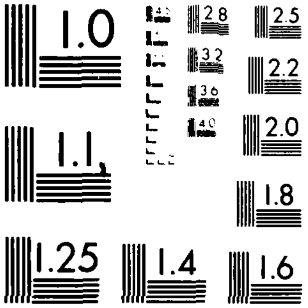
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DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Maryland 20084

CMLD-83-20

ROBOTICS: AN INTRODUCTION TO TODAY'S
ROBOT AND FUTURE TRENDS

by

Kevin R. Scully

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Computation, Mathematics, and Logistics Department
David W. Taylor Naval Ship Research and Development Center

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ROBOTICS: AN INTRODUCTION TO TODAY'S ROBOT AND FUTURE TRENDS

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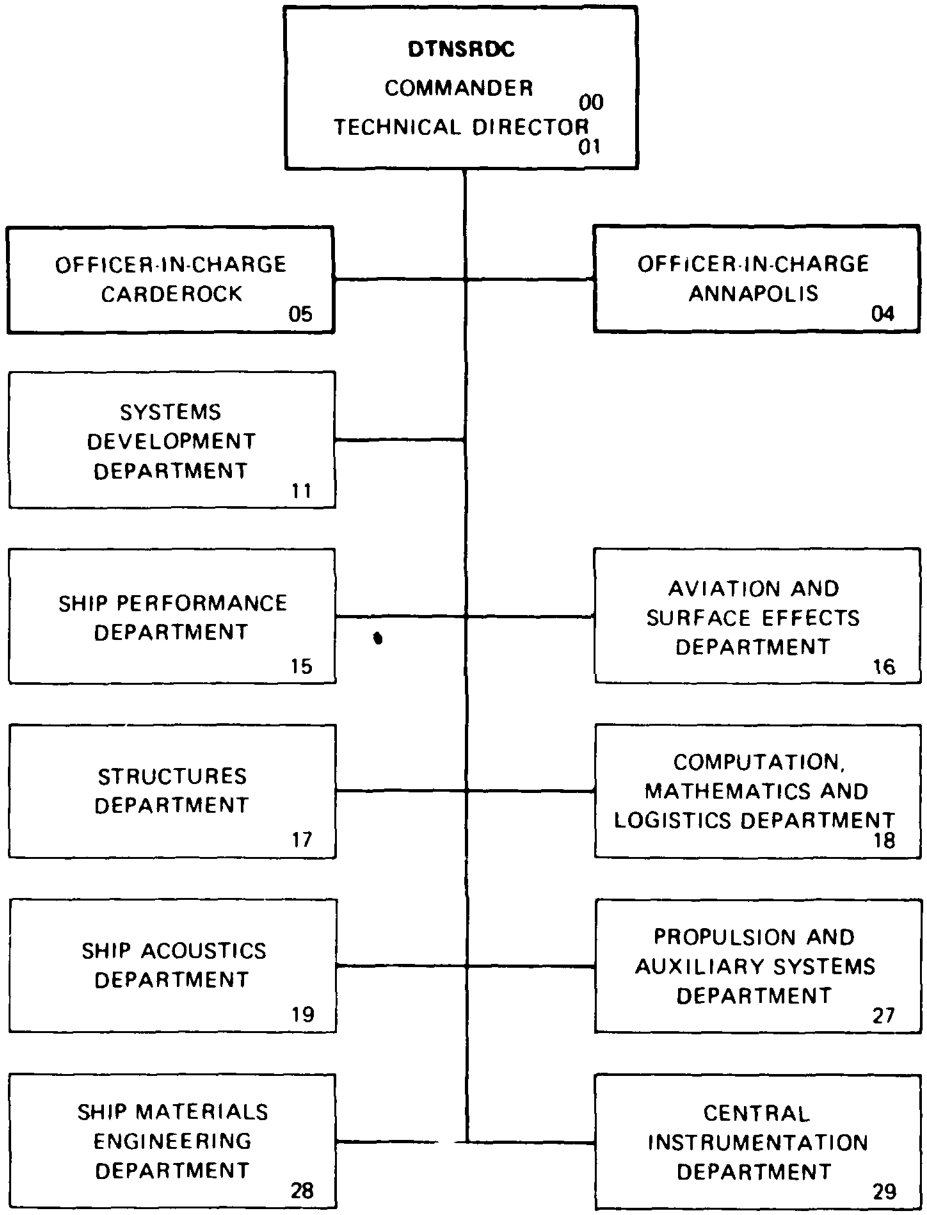

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A robot consists basically of three components: the power supply, the mechanical unit, and the controller--a microprocessor or minicomputer. The complexity of the control center determines the capabilities of the robot, which vary from material handling, painting, welding, and non-destructive testing, to identifying a given object in a random collection of objects and assembling it with other parts into a complex device. As features such as vision, tactile sensing, mobility, and CAD/CAM move from the research (over)

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laboratory to the factory floor, robot capabilities will become virtually unlimited. There are three programming techniques available with today's robot: (1) manual lead-through programming; (2) teach pendant programming; and (3) textual language programming. Textual language programming may be done off-line, whereas the other two programming methods are done on-line.

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ABSTRACT

A robot consists basically of three components: the power supply, the mechanical unit, and the controller--a microprocessor or minicomputer. The complexity of the control center determines the capabilities of the robot, which vary from material handling, painting, welding, and non-destructive testing, to identifying a given object in a random collection of objects and assembling it with other parts into a complex device. As features such as vision, tactile sensing, mobility, and CAD/CAM move from the research laboratory to the factory floor, robot capabilities will become virtually unlimited.

There are three programming techniques available with today's robot:

1. Manual lead-through programming.

2. Teach pendant programming.

3. Textual language programming.

Textual language programming may be done off-line, whereas the other two programming methods are done on-line.

ADMINISTRATIVE INFORMATION

The work reported here was performed in the Computer-Aided Design and Manufacturing Division of the Computation, Mathematics, and Logistics Department, under in-house funding.

INTRODUCTION

The importance of robots in industry is succinctly summarized in the following quote by Ewald Heer:[(1)*]

> "If, as many believe, the 1960's were the decade when numerical control (NC) came to maturity, and the 1970's were the decade of the computer, and, in particular, computerized numerical control (CNC), the 1980's promise to be the decade in which the robot achieves maturity and full acceptance in industry, and takes over many boring and dangerous jobs now done by humans. The basic reason is its cost effectiveness. Typically, one robot can displace three or four workers, and reduce labor costs by as much as 80 percent. Over 30,000 are already at work in many industrial and non-industrial applications."

What qualities define a machine as a robot? The Robot Institute of America defines a robot as follows:

> "A robot is a reprogrammable multi-function manipulator designed to move material, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks."

To be more specific, advanced robots in use today have two distinguishing features. First, all are jointed, metal arms controlled by a computer. They may have two joints or six, which may or may not have the same functions as human joints. For example, Unimation, Inc., manufactures a robot with a spinning wrist. Second, and this is the key feature, robots are reprogrammable and hence versatile. An automatic lathe is not a robot no matter how sophisticated it is or how many switches and knobs it has, because it can do nothing but turning operations. Some robots may weld today, spray paint tomorrow, and load boxes the following day. (See Figure 1, which depicts T3, a robot built by Cincinnati-Milacron.) One needs only to reprogram the robot and put a new

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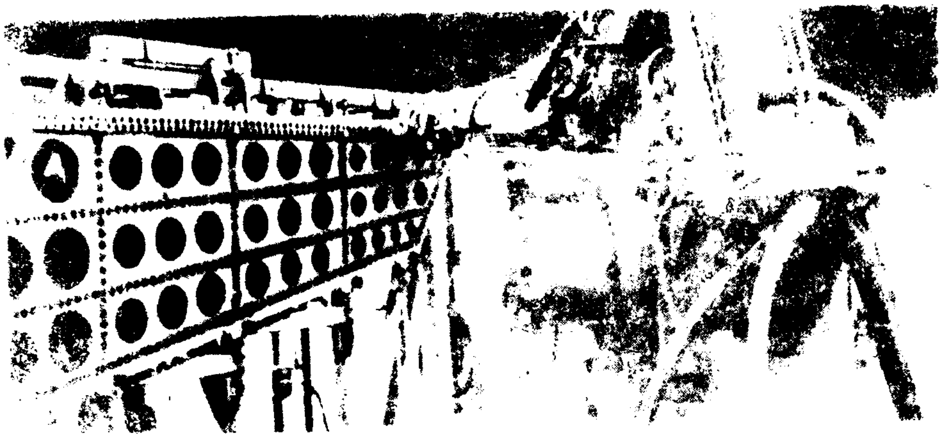
* A complete list of references is given on page 37.



a. [illegible] automatically changes six different drill heads as it expertly handles the [illegible] den [illegible] drilling [illegible] quality hole[s] in graphite-epoxy vertical fin skins for the F-16 multi-role fight plane. Result: Productivity increase of better than [illegible] [illegible] metals.

b. [illegible] 13 Robots vent compressed sand cope molds using their six axes of motion to provide the absolute straight line needed to avoid rod bending and mold "breakout." The robots constantly check for rod straightness, identify each mold, give appropriate "cycle-begin" signals, and [illegible] interl[illegible] [illegible] line in this unusual [illegible] application.

c. In this automatic body checking system, [illegible] not only provides fast, automatic check of all critical car body openings to .020" accuracy, but supplies data an average tool engineer can readily analyze. System's speedy identification of dimensional trends/errors gives assembly people more [illegible] time to make corrections, [illegible] [illegible] levels, fewer defects [illegible] [illegible]irs, and lower warranty [illegible] (Cincinnati-Milacron)

Figure [illegible] [illegible] Applications hand on the end of its arm(s).* There are many alternative hands, which are termed end-effectors: welding guns, paint sprayers, riveters, claws, scoops. (See Figure 2.)

The Robot Institute of America, an industry trade group, places the number of actual U.S. robot manufacturers at 40. Some manufacturers produce as many as five different models of robots, hence a large variety of robots exists in the U.S. today. The wide spectrum of robots is demonstrated by the following comparison. Microbot, Inc., manufacturers a robot, the Mini-Mover, with an 18" reach, a 1-pound payload, and a cost of approximately $2500. At the other end of the spectrum, Cincinnati-Milacron's hydraulic T3 Robot has a reach of 12'10", a payload of 225 pounds, and costs approximately $100,000.

Robotic advances, refinements, and applications have made significant progress in the past ten years. New developments in advanced manufacturing automation technologies are being quickly integrated into the robotics industry with reasonable expectations for substantial long-term productivity improvements. The reason for the recent surge in robotics is easily seen by comparing the advantages of current robot installations with the disadvantages. The advantages are summarized as follows:

1. Increased manufacturing productivity
2. Increased product quality
3. Lowered labor and material costs
4. A 24-hour robot work day, without breaks
5. No vacations, pensions, retirement pay, health insurance, pay raises, etc., no strikes

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* The hand(s) of a robot is(are) a specialized tool.

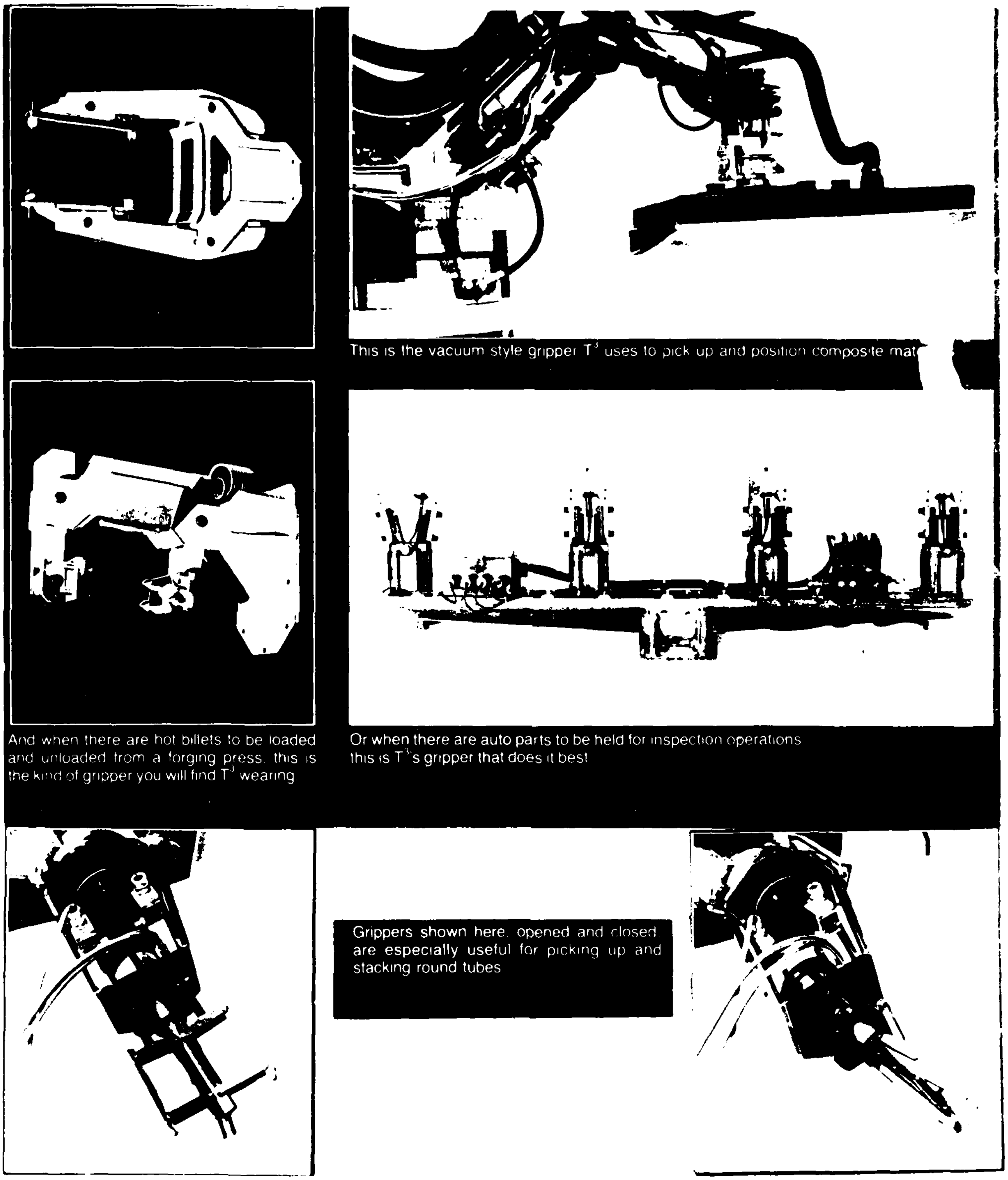

Figure 2 - Robot End-Effectors (Source: Cincinnati-Milacron)

6. Robot immunity to Government and union regulations applicable to humans respecting heat, fumes, noise, radiation, and other safety hazards.

The principal disadvantage or deterrent to robot installations is the high initial investment. The larger, more advanced robot systems will cost a minimum of $100,000.* As a guide, the basic robot, with its base power supply, control, and end effector will represent about 55% of the total system cost. Accessories and fixturing account for about 30%, and installation and interfacing costs average 15%. However, some companies are realizing a 100% return-on-investment in as little as one year.

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* A caveat for robot purchasers: the advertised price for a robot is approximately one-half of the total cost which must also include accessories, peripheral interfaces, and installation.

THE COMPONENTS OF A ROBOT

Basically, a robot consists of three components:

1. The Power Supply
2. The Mechanical Unit
3. The Controller

The power supply, mechanical unit, and controller are shown in Figure 3 from left to right, respectively. The power supply is the power source for the robot. Three types of power sources are available, depending on the user's need: a hydraulic power unit, an electric power source, and a pneumatic power unit. Electric power sources are required to power electric actuators and some types of hydraulic and pneumatic actuators which require pumps to circulate the fluid. Hydraulic and pneumatic power sources have the same type of power system except for the active fluid. Also, hydraulic power sources power hydraulic actuators, and pneumatic power sources power pneumatic actuators. Possible power sources for the future may include solar cells and nuclear energy.

The mechanical unit or manipulator is the component which moves and executes the sequence of operations as instructed by the user via the control center. Some definitions pertaining to the mechanical hardware are listed in the Appendix.

Each axis of movement by the manipulator is controlled by an actuator. Hence, a six-axis robot has six actuators. The respective advantages and disadvantages of the three types of robot actuators are given here:(2)

Hydraulic Actuators

Advantages	Disadvantages
1. Large lift capacity	1. Expensive
2. Moderate speed	2. Pollute work space with fluids and noise

Figure 3 – Robot Manipulator with Power Source and Control Center
(Source: [illegible])

Advantages	Disadvantages
3. Oil is incompressible: hence, once positioned, joints are motionless.	3. Unsuitable for high speed
4. Accurate control	

Pneumatic Actuators

Advantages	Disadvantages
1. Relatively inexpensive	1. Compressibility of air limits accuracy
2. High speed	2. Noise pollution still exists
3. Do not pollute work space with fluids	3. Leakage of air is major concern
	4. Additional air filtering system and drying system needed

Electric Actuators

Advantages	Disadvantages
1. Fast and accurate	1. Requires gear trains or the like for the transmission of power
2. Capability for sophisticated control techniques	2. Gear backlash limits precision
3. Easily available and relatively inexpensive	3. Electric arcing may be a problem
4. Simple to use	

Typically, a manipulator, sometimes termed a robot arm, is able to move about three axes: in and out, up and down, and around. These movements can also be referred to as x, y, and z coordinates; as elbow extension, shoulder swivel, and arm sweep; or by other designations. The wrist adds another three axes of motion. Motions of the wrist include yaw, pitch, and roll, as shown in Figure 4.

The control center is the vital link in a robot system. The controller has a threefold function: first, to initiate and terminate motions of the manipulator in a desired sequence and at desired points; second, to store position and sequence data in memory; and third, to interface with external devices. Robot controllers can be step sequences, microprocessors, or mini-computers.* The complexity of the control determines the capabilities of the robot. In order of increasing sophistication, robots fall into the categories of non-servo controlled, servo controlled, and sensory robots.[3] The essential difference between non-servo controlled and servo controlled robots is the presence of feedback loops in servo controlled robots. Sensory robots are servo controlled, but, in addition, they utilize external sensors which free the robot from dependence on support equipment.

NON-SERVO CONTROLLED ROBOTS

Non-servo controlled robots, which are the simplest, move their arms in an open-loop fashion between exact endpoints on each axis or along precisely determined trajectories in accordance with fixed sequences. A non-servo controlled robot is controlled by mechanical stops and/or limit switches.

The motions of a non-servo robot are limited by mechanically adjustable stops on each mechanical joint or axis. Each axis can therefore move in an open loop fashion to only two positions. A sequence control uses stepping

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* An offshoot of the controller is the teach pendant, shown in the caption in Figure 5. The teach pendant is used to record movements required of the robot manipulator.

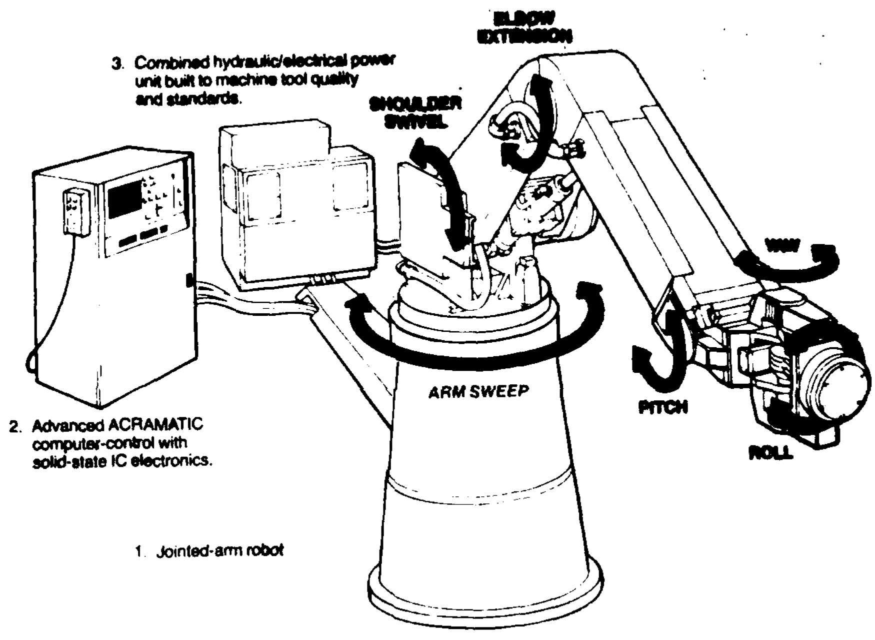

Figure 4 - Robot Displaying 6-Axis Maneuverability
(Source: Cincinnati-Milacron)

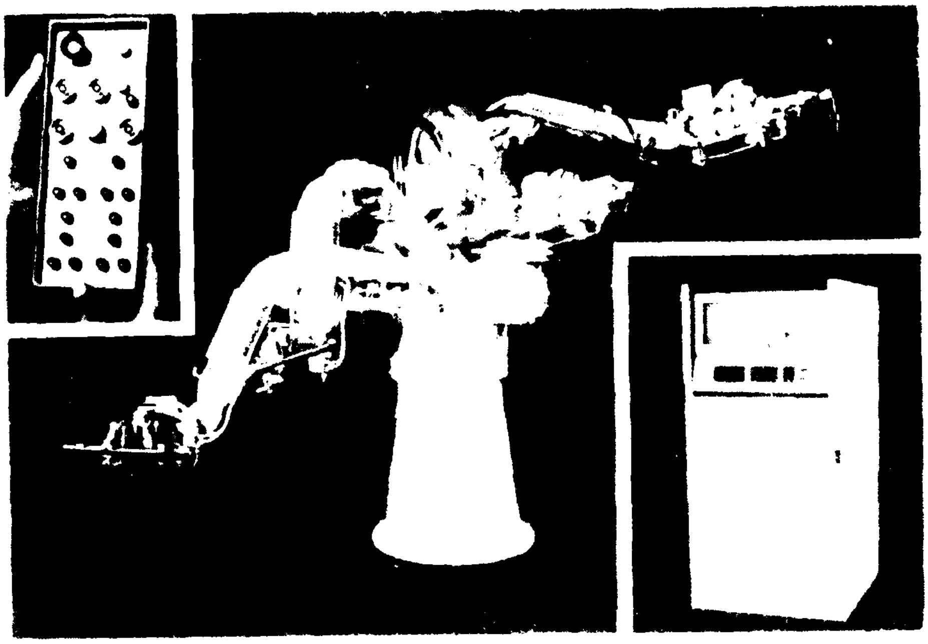

Figure 5 - Robot Manipulator with [illegible] control center
[illegible] Cincinnati Milacron

switches or pneumatic logic sequencers capable of executing single problems of about 24 consecutive steps, or electronic programmable controllers with greater program capacity. In addition to initiating the motions of the manipulator, these controls also transmit and receive signals to and from other equipment with which the robot operates.

In a limit-switch-controlled robot, more than one position can be defined along an axis by indexable stops inserted or withdrawn automatically. A sequence-type control steps through a number of preset logic steps, causing one or more joints to move until the appropriate limit switch on the axis is reached.[3]

Because of inherent limitations in their control sequence characteristics, non-servo robots usually serve special purposes. The most common application of non-servo robots is material handling, such as moving an object from point A to point B. The Motion Mate, shown in Figure 6, is an example of a non-servo robot. The Motion Mate is pneumatically operated and has 4-axis movement. This robot is often termed a "pick-and-place" robot. Some robot "experts" do not think these manipulators should be classed as robots.

SERVO CONTROLLED ROBOTS

Servo controlled robots have internal sensors--position, velocity, acceleration, force, and torque sensors--that measure the internal states of the manipulator, compare these measured states with predetermined operational parameters of the control program, and transmit deviations to the servo system for corrective action. With appropriate quality of the internal sensors, the controllers, and motors, these systems can be operated with high precision (.04 inch to .004 inch position repeatability) and high speed. Also, they can operate, for all practical purposes, over an infinite number of points enclosed

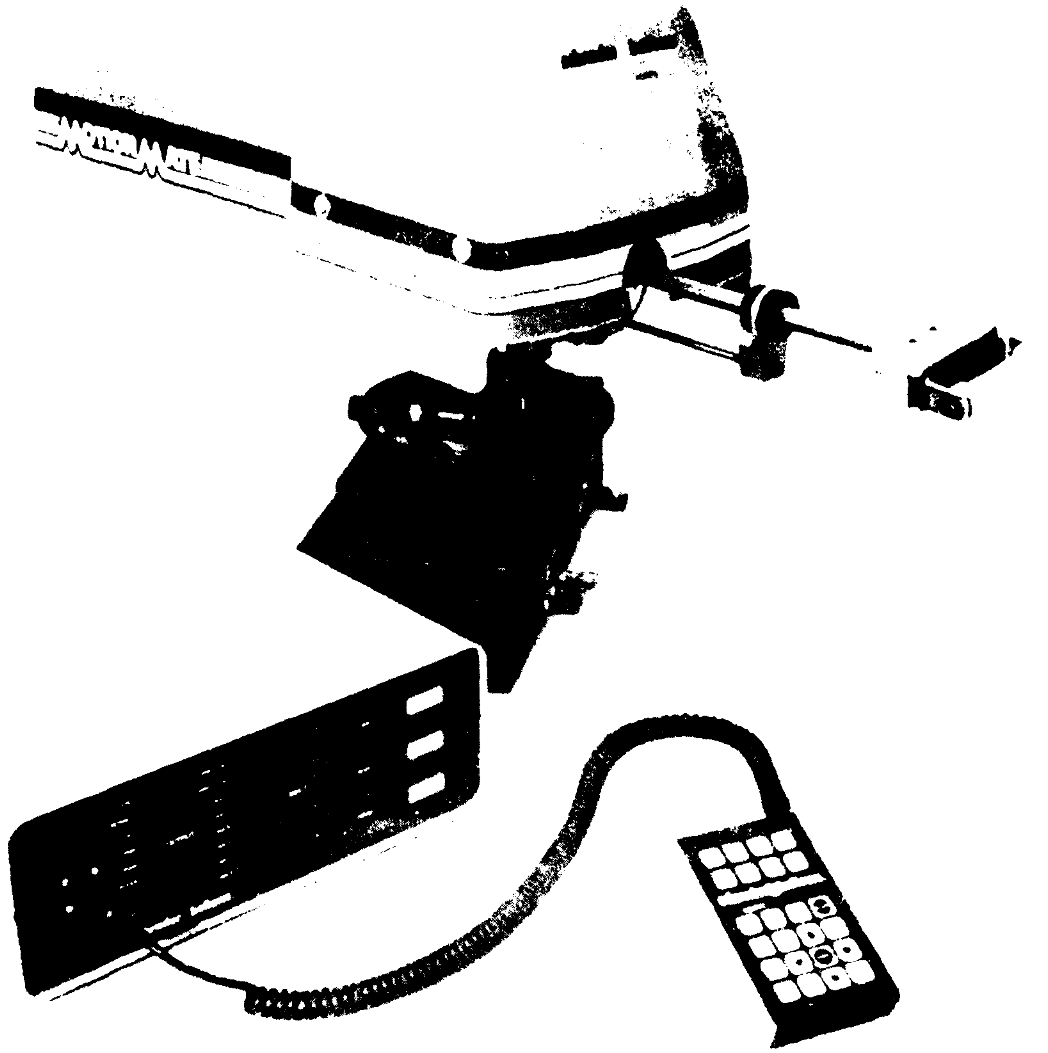

Figure 6 - The Motion Mate with Controller and Teach Pendant
(Source: Schrader-Bellows)

in the envelope of operation. Typical applications for servo controlled robots include spot- or arc-welding, painting, finishing, assembly, non-destructive testing, drilling, cutting parts, material handling, or any combination of these applications. Servo controlled robots are further divided into point-to-point control and trajectory control robots.

A point-to-point robot is given the start and end points that must be passed on each axis. During motion between these points there is no prescribed functional connection among the various axes, and no defined trajectory is maintained by the end-effector.(4) Generally, robots of this type are taught by moving the arm physically through the required sequence of motions and pushing a "record this point" button which the controller records. When all points and functions have been recorded, the controller is put on automatic, and the robot will go through the sequence itself. The path taken between the recorded points is independent of the path taken during the teaching sequence. Most robots in use today are point-to-point controlled.

Under trajectory control, all points between the start and end points are predetermined and given, thus enabling motions along straight lines, circles, spirals, and arbitrary curves. The programmer specifies the path to be taken by putting the controller in the record mode and moving the arm through the desired path, either by hand or using a joystick. Trajectory control robots, sometimes called "continuous path robots," are generally smaller than point-to-point robots. They are commonly used for spray painting, arc welding, polishing, grinding, and assembly work.

A more sophisticated type of servo controlled robot has more flexibility than the simpler types and is capable of approximating the motions of a human arm. These robots possess highly flexible and programmable manipulators and utilize controllers with the highest level of artificial intelligence used in industrial automation. Such controllers can be interfaced with sophisticated sensory and inspection devices and also enable the robot to be taught even the most complex jobs with relative ease.[5] The Unimate PUMA robot and the Cincinnati Milicron T-3 robot are examples of this type. The T-3 is mounted on a pedestal 1.5 meters high which can swivel the arm through 250 degrees. The arm can swivel vertically at the shoulder through 90 degrees. The robot can carry heavy loads of up to 80 kilograms (176 pounds) at full speed and up to 135 kilograms (298 pounds) at reduced speed. It can calculate automatically the shortest route between any two points, can call on a number of programs from its memory, and is capable of continuous as well as point-to-point motion. Figures 7 and 8 illustrate two current applications of the Cincinnati-Milacron T-3 robot. In Figure 7, the robot spot-welds an automobile frame. In Figure 8, a single robot transferring a transmission case is shown, but a total of eight robots are interfaced into this automotive part storage system. In an eight-hour shift, each robot will handle approximately 20 tons of transmission cases, for a 5% to 10% increase in productivity.

At the General Dynamics plant in Fort Worth, Texas, one of Cincinnati Milicron's T-3 robots makes sheet metal parts for the F-16 fighter airplane. The T-3 selects bits from a tool rack, drills a set of holes to a .005-inch tolerance, and machines the perimeters of 250 types of parts. A man doing the same job can produce six parts per shift, with a 10% rejection rate. The robot makes 24 to 50 parts, with zero rejections. The machine costs over $60,000 but has saved $93,000 in its first year of operation.[4]

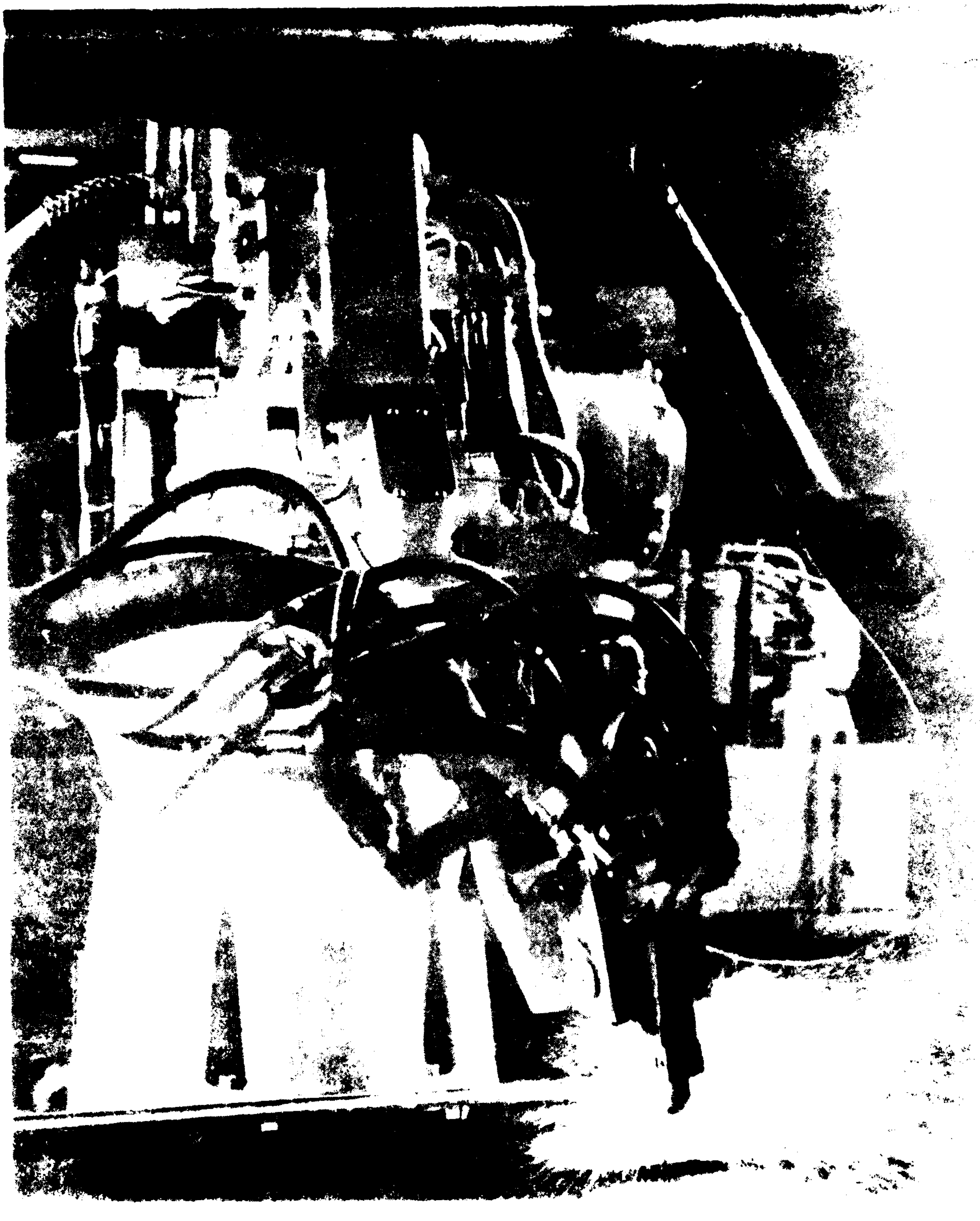

Figure [illegible]

SENSORY ROBOTS

Sensory robots are the most sophisicated type of universal robot. In addition to internal sensors, they utilize external sensors--TV cameras, pressure detectors, magnetic sensors, laser range finders, force-torque sensor, and the like. These external sensors determine the robot's relation to its surroundings and, in particular, the location of parts to be handled. The sensory data are monitored by the control computer. It can modify programs to cope with changing requirements and unpredictable situations, such as a random collection of parts. Because sensory robots are able to recognize changes in their environment and make control corrections to perform reliably in the new situation, these robots may be called "intelligent." An example of a robot-vision system is shown in Figure 9, where the camera is located directly above the weld gun.

One of the most advanced robots of this type is produced by Hitachi, Japan. It has two arms, each with eight degrees of freedom. Using seven television cameras, it can identify a given object in a random collection of objects and assemble it with other parts into a complex device, such as a vacuum cleaner, in a few minutes.

Fisher Body Division of General Motors has recently installed a robot system believed to be the first of its kind in the United States, and maybe in the world. Four Cincinnati Milicron robots are used in conjunction with Robotic Vision System's 3-D optical system to assemble windshield post joints and weld roof-to-quarter panel joints on General Motors passenger cars. The robot's vision system, located on its wrist, is able to locate each seam in space to within .001 inch as it is swept over the part to be welded. The information gathered during the sweep pass is processed so the following welding pass will adapt to seam variations in shape and location. This adaptive feature allows

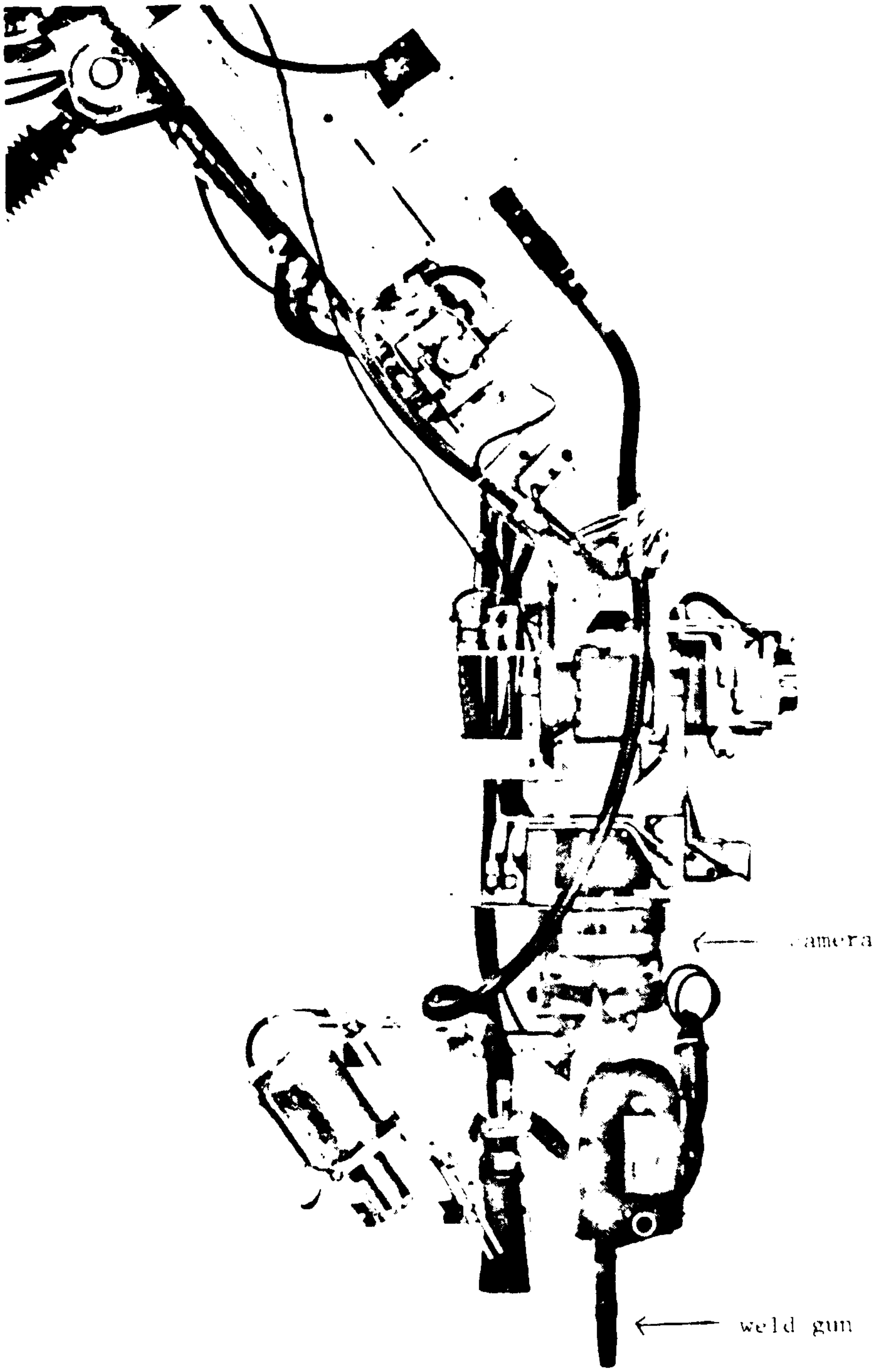

Figure 9 - A Welding End-Effector with Vision
(Photograph taken by SRI International)

the system to regulate welding current, welding velocity, and the feed rate of the silicon/bronze welding wire according to the characteristics of the seam. The welding process can adapt to seam locations in error as much as 0.25 inches.

PROGRAMMING

Two mainstreams of software organization have been pursued for the control of robots. The first is the "explicitly programmed" system, which makes the user primarily responsible for every control action and requires explicit instructions. The second type is "world modeling," which makes the robot system responsible for knowing specific facts about the objects it works with. Explicitly programmed systems force the user to decide exactly what sequence of library routines the robot must use to perform a given task, whereas world modeling systems make some of the decisions based on a more goal-oriented description of the task.[6]

Software systems in industrial use are the explicitly programmed type. Although world modeling software is the trend for future robot systems, the demand on present industrial systems is to support user needs. Features such as ease of programming and debugging, an English-like command language, flexibility for extensions, supplements to computer-aided design (CAD), and vision systems are a few of the important requirements. Three programming techniques are available with toaay's robot systems:

1. Manual Lead-Through Programming
2. Teach Pendant Programming
3. Textual Language Programming

MANUAL LEAD-THROUGH PROGRAMMING

All motion points are stored into memory (disks, tapes, etc.) by leading the manipulator through the desired motions. The major advantage of this type of software system is the ease of program application. The operator is required only to set the correct switches and pushbuttons on the control panel and then manually lead the manipulator through the required motions. Manual lead-through programming is synonymous with trajectory control of robots. No knowledge of a robot language is required. This programming technique does have a major drawback. Editing is limited because many points are recorded to produce the continuous path. Editing would create discontinuities in the path; thus the only way to edit the path is to reprogram it by leading the manipulator through the desired motions.[6]

TEACH PENDANT PROGRAMMING

This programming system is the most common on industrial robots. In addition to the three basic components of a robot (the manipulator, the power source, and the controller), this system includes a teach pendant used solely for programming.

To teach a task, the teach mode is initiated by setting the correct switches on the control panel. The manipulator is moved and the position is recorded by pressing the record button on the teach pendant. Various parameters such as gripper state, time delays, output states, wait for inputs, and travel speed can be set and recorded. Unlike the manual lead-through technique, which records the complete path, this teach technique records only the end states of the path. When the robot is in operation, the path between successive end points depends on the control algorithm. Teach pendant programming is synonymous with point-to-point control of robots. In the more advanced robots, the operator can specify straight-line motion, circular-arc interpolation, or joint interpolated and/or continuous path motion.

The most important advantage from the user's perspective is the large number of functions, such as time delay, output signed states, and travel speed, that can be programmed. Another advantage is that the editing capability is superior to that of the manual lead-through technique. Also, because discrete endpoints are programmed, the mass memory capacity allows for longer programs.

The disadvantages of the teach technique are that it generally restricts the operator to simple programs with limited branching capability, there is no easy means of documentation, and, for most robot systems, these programs have to be taught on-line.(6)

TEXTUAL LANGUAGE PROGRAMMING

In non-textual techniques of programming, the operator programs the robot by leading it through the operation, either manually or by means of a teach pendant. However, because of the complexity of assembly-type applications, most industrial robots are equipped for textual programming. Textual language programming is an off-line programming method via cards, tape, or a terminal. Some robot programming languages in use today are: AL, developed by Stanford; AUTOPASS, developed by IBM; and LAMA, developed by MIT. This programming technique provides instructions for moving the manipulators, reading sensors, sending signals to external equipment, setting counters, and performing logical branching, as well as many other instructions which simplify the procedure for programming a robot.

In textual programming, all operations must be described symbolically in the correct sequence and with the required precision indicators. Thus, all manipulator and robot positions and motions must be determined beforehand by elaborate measuring processes. To avoid these difficulties, techniques similar to the manual lead-through or teach pendant methods are often used to determine the geometrical data required in textual programming. Although textual programming requires more forethought and appears to be more elaborate and expensive, it is gaining progressively greater importance in practical applications. Reasons for its use include the greater complexity of modern production systems, which include robots; the proliferation of sensor systems and associated evaluation of sensor data; the possibility of modularizing the software structure to effect changes easily; the ability to prepare programs off-line; and the production of readable documentation.[1]

User advantages in the textual language teaching methods include all of the typical advantages of the teach pendant methods such as editing and special function commands. In addition, features such as logical branching and use of data structures provide useful tools for developing large and complex programs. In general, these programs tend to be self-documentating, and a hard copy can easily be obtained.

The disadvantage of a purely textual mode of programming is that it restricts the user to communication through a terminal. In complex assembly applications this method is the most efficient to program, but for many process-type applications a combination of the teach pendant or lead-through technique with a textual language format proves more efficient.[6]

FUTURE TRENDS

Since low cost data processing and computing power for automation are now commonplace, robotic applications that were previously technologically possible but not economically feasible in assembly operations are now much more easily cost-justified. Their impact on low and medium volume batch manufacturing operations could be tremendous.

The following features are considered desirable goals for future robots:

1. Vision
2. Tactile Sensing
3. Mobility
4. Hand-to-Hand Coordination
5. General Purpose End-Effectors (Hands)
6. Man-Robot Voice Communication
7. Interaction with Other Technologies, such as CAD
8. Self-Diagnostics
9. Energy Conserving Design

When these features have been developed so that they are both reliable and economical, they will provide considerable extension to the scope of robot applications.(7)

VISION

Robots that can "see" will play a large role in assembly, quality control, inspection, welding, painting, and many other applications. Such robots will be able to identify and reject defective parts, realign misoriented parts, detect missing components, follow contours and weld seams, adjust to changing conditions, and otherwise handle situations that would baffle "blind" robots.(8)

In robot vision systems, a television camera feeds images to a computer which converts the images to digital code. This digital representation is then compared with other images stored in computer memory. The part type is determined when two of the codes are matched (pattern recognition). For example, the Consight-1 Robot at General Motors Corporation can recognize, grasp, reorient, and transfer five different part types on a moving conveyor.[9] Another example is the General Motors robot system, mentioned earlier in the section on sensory robots, which analyzes the weld seam and adjusts for variation in shape and location.

The Univision I system of Unimation, Inc. also uses pattern recognition data to identify the part to be picked up. This system can recognize nine different objects and a total of 12 parts in the field of view at one time. For each part, a number of distinguishing features can be portrayed: area, perimeter, center of gravity, number of holes, and maximum and minimum radii.[7]

Experts predict that future robots may be able to recognize objects they have never seen before. Computers for these advanced robots would use deduction to determine the meaning of shapes in the same way that the human brain reaches conclusions about new objects. This area of artificial intelligence is in the early stages of development. However, researchers believe such robots with vision and deductive capabilities could appear in laboratories by the mid-1980's and could be operating on the shop floor by 1990.[9]

TACTILE SENSORS

Researchers are also developing artificial tactile sense for robots. Although vision may guide the robot arm through many manufacturing operations, it is the sense of touch that will allow the robot to perform delicate gripping and assembly operations. Some researchers predict that force sensing will become more useful in the future than vision. Tactile sensors will provide position data for contacting parts more accurately than that provided by vision.

Tactile sensors allow a robot to adapt to changing situations. A tactile sensor gives a robot a sense of "touch" by measuring forces such as torque, pressure, weight, resistance, etc. Tactile sensors can be as simple as a limit switch, proximity sensor, or an LED/photocell pair that determines whether the part is present, or they can be as complex as Stanford University's three-fingered "hand" that (when developed) will be so sensitive it can catch a thrown ball.[8]

Advanced tactile sensors exist mostly in the laboratory or on drawing boards, but an IBM robot uses tactile sensors to assemble a gear drive mechanism. The IBM robot uses tactile sensors--force gauges on each axis of the gripper--to detect errors and a special adaptive control program that has multiple solutions for each problem. When a problem occurs, the robot diagnoses the situation and tries several solutions.

IBM has a videotape of their assembly robot encountering a number of problems--gears that will not mesh, parts that do not fit, misaligned components, and so on--and it solves each problem. The robot nudges, taps, turns, wiggles, and maneuvers the parts in such a way that a viewer could easily be convinced a human operator was guiding the process[8]

MOBILITY

A compact mobile robot would require less factory modification and could move in complex paths, access large areas economically, and easily handle intermittent or asynchronous demands. Machine loading and servicing, clean room material handling, routine cleaning, and maintenance are possible application areas.

A great deal of research is being done in the area of mobile robots, but this work has yet to progress past the laboratory stage. Mobile robots will be available by the end of the decade, bringing us closer to the unmanned factory and improved productivity.[7]

INTERFACING WITH CAD/CAM

Another major step toward a completely automated manufacturing process will occur when a robot is integrated with a Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM) system. This development will enable a design engineer to set up robot command sequences from the CAD CRT, simulate robot motions, detect and solve errors, and download the final control program to the robot.[8]

In general, programming a robot in a CAD/CAM environment is analogous to programming an NC machine tool. The parts to be assembled or machined are already stored in the CAD/CAM data base. Other equipment such as machine tools and conveyors may have been designed and stored on the system as well.

The next step is to program the robot's path graphically to perform the manufacturing operation. A simulation of the entire system showing robots, parts, machine tools, and conveyors can verify the overall process and identify potential interference problems and collisions. The system could also automatically generate new robot programs to handle new or changed products without a delay in the manufacturing process or loss of production time of expensive capital equipment.[7]

Some work has already been done along these lines. Some CAD/CAM systems can determine where robots should be positioned for maximum effectiveness in welding a car body. Both Unimation, Inc. and Automatix have connected their robots to Computervision CAD systems for trade show demonstrations. McDonnell-Douglas Automation Company has successfully connected its CAD/CAM system to machine tools.[8]

When it is possible for robot manufacturers and users to produce robot commands from a CAD/CAM system, robots will cease to be just islands of automation; instead, they will be fully integrated parts of the automated factory.

CONCLUSION

Robots at various stages of mechanical complexity and intellectual sophistication are rapidly becoming important elements in industry. In industry, the primary driving force is increased productivity. In other applications, robots become necessary because the work site is remote, dangerous, or inaccessible to humans. Although applications for robots are varied and manifold, many fundamental research problems are very similar, centering on vision, tactile sensors, mobility, artificial intelligence techniques, and peripheral interfaces. The importance of peripheral interfaces is being increasingly recognized: For an average industrial robot installation project, it will usually cost as much to interface with external devices, engineer, and install the robot as it will cost to purchase the robot itself.

After a decade of uncertainty and hesitation, American industry is moving toward automation and is adopting robots as vital elements in the production process. Within reach are computer controlled systems of robots and other complex machines that promise unprecedented gains in productivity.

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APPENDIX A

GLOSSARY

(Source: Smith, B.M., "A Glossary of Terms for Robots")(10)

1. Base. The platform or structure to which the shoulder of a robot arm is attached.

2. Shoulder. The joint or pair of joints which connect the arm to the base.

3. Joint. A rotational or translational degree-of-freedom in a manipulator system.

4. Arm. An interconnected set of links and powered joints comprising a manipulator which supports or moves a wrist and end-effector.

5. End-Effector. An actuator, gripper, or mechanical device attached to the wrist of a manipulator by which objects can be grasped or otherwise acted upon.

6. Wrist. A set of rotary joints between the arm and end-effector which allow the end-effector to be oriented to the work piece.

7. Actuator. A motor or transducer which converts electrical, hydraulic, or pneumatic energy to effect motion of the robot. A robot normally has one actuator for every degree of freedom.

8. Servomechanism. An automatic control mechanism consisting of a motor driven by a signal which is a function of the differnce between commanded position and/or role and measured actual position and/or rate.

9. Servovalve. A transducer with a low energy input signal of which the output is a higher energy fluid flow.

10. Peripheral Device. Any piece of computer equipment apart from the central processing unit and man-memory system.

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